TENSILE, CREEP AND FATIGUE PROPERTIES OF LIGA NICKEL STRUCTURES

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ABSTRACT

Elevated temperature tensile, creep and high cycle fatigue properties of electro-deposited LIGA Ni structures have been measured and are being used to predict the reliability of LIGA based MEMS structures. Microsamples with dimensions of 100's of microns have been LIGA fabricated and characterized in terms of their elevated temperature tensile and creep strength and their high-cycle fatigue performance. The strength of these LIGA Ni structures was found to decrease dramatically at temperatures above 200°C. At stresses significantly below the yield strength, substantial creep deformation was also observed at moderately elevated temperatures. The fatigue life of the LIGA Ni microsamples increased with decreasing stress amplitude in a manner comparable to what has been reported for wrought Ni. An apparent fatigue limit was observed for the LIGA Ni microsamples, but the importance of component geometry on the fatigue life was also highlighted.

INTRODUCTION

LIGA (an acronym from the German words for lithography, electroplating, and molding) is a micromachining technology used to produce microelectromechanical systems (MEMS) made from metals, ceramics, or plastics [1]. In this technique, X-rays are used to carve deep patterns into a resist and these patterns are filled through electroplating. LIGA allows the fabrication of structures, which have vertical dimensions on the order of hundreds of microns while maintaining side-wall dimensions of 0.1 micron/millimeter. The resulting height-to-width ratio capability is relevant to the manufacturing of MEMS components that can withstand high pressures and temperatures, and LIGA Ni structures are being considered for use in fusing/safeing and arming devices, micro-turbines and high temperature heat exchangers. The importance of elevated temperature properties can also be related to the fact that self-resistive heating and thermal expansion are often used for component activation. The successful application of LIGA processed components will require an understanding of the full range of mechanical properties.

The room temperature tensile behavior of LIGA Ni structures have been characterized in a growing number of studies, see for example [2-5]. It is generally acknowledged that electroplating conditions have an important effect on both the underlying microstructure and the mechanical properties of LIGA Ni structures. The development of crystallographic texture has been shown to affect the in-plane Young's modulus [3,5], and reduced grain sizes have been related to increased room temperature strength [3,4]. The elevated temperature properties and long-term fatigue resistance of these structures is much less well understood.

EXPERIMENTAL PROCEDURES

Dog-bone shape microsamples were prepared using the LIGA process at the Center for Advanced Microstructure & Devices (CAMD). The microsamples were electrodeposited into PMMA molds using a commercially available Ni-sulfamate solution operated at a pH of 3.5-4, a bath temperature of 55°C, and a current density of 20 mA/cm^2. Each microsample has overall dimensions of 3.7 mm by 1.9 mm and was deposited to a thickness of approximately 400 μm, which was 100 μm thicker than the PMMA molds. The over-plated material was removed and the top and bottom faces of the microsamples were mechanically polished to a mirror finish before testing. The gage widths of these specimens were varied from 100 to 500 μm.

Tensile tests were conducted using the microsample tensile machine and non-contact interferometric strain displacement gage (ISDG) first introduced by Sharpe [6] and more recently modified for elevated temperature use by Zupan [7]. The microsamples were heated resistively with a low DC voltage and test temperatures were monitored with a two-color pyrometer. Tensile loading was accomplished through the use of a piezo-electric actuator, and strain was measured with the ISDG. Creep tests were conducted using the tensile test frame, but the stress was applied with a dead load instead of the piezo-electric actuator. A microsample fatigue test machine was developed for this study. This machine consists of a voice-coil actuator, linear slider, grips and dynamic load cell, as shown in Fig. 1. Fatigue tests were conducted with sinusoidal tension-tension load cycles that employed an R ratio of 0.1 and frequency of 200Hz.

RESULTS AND SUMMARY

A typical stress-strain curve of the room temperature tensile behavior of the LIGA Ni microsamples tested in this study is shown in Fig. 2. Young's modulus was measured in the

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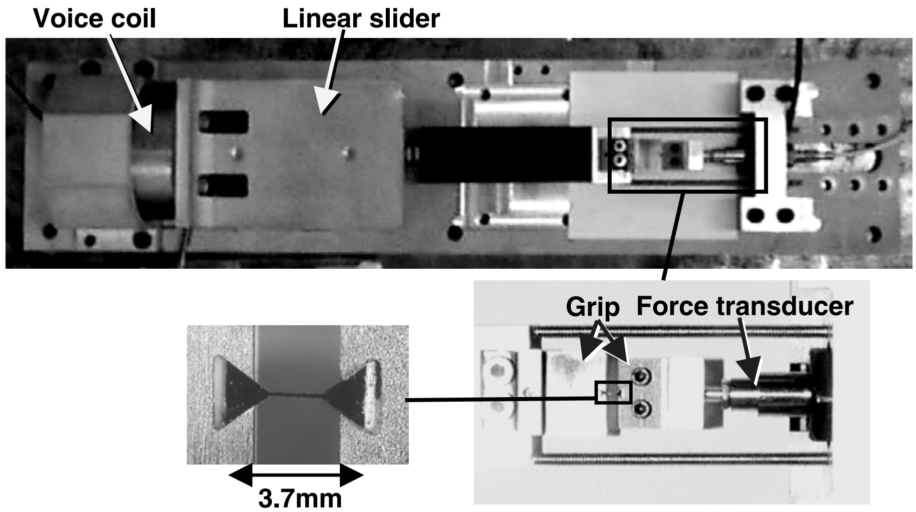

Fig. 1. Microsample fatigue test machine consisting of the voice-coil actuator, linear slider, grips and a dynamic force transducer. The grips were designed so that the taper of the microsample fits directly into the matching wedge shape of the grip.

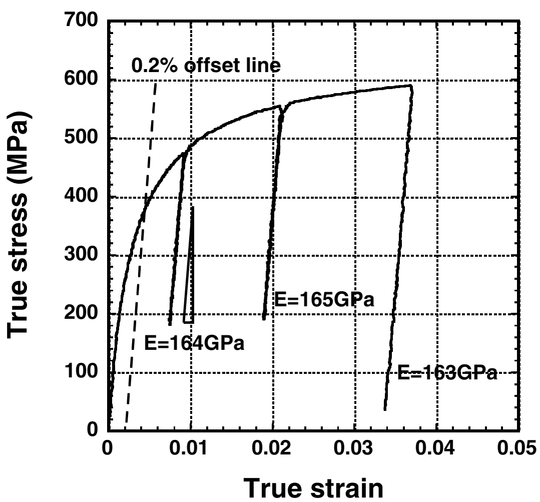

Fig.2. A typical room temperature stress-strain curve obtained by the microsample tensile tesing. The modulus was measured from the unloading curves.

unloading portions of the curve, as is shown in Fig. 2. The Young's modulus was found to be 163±14 GPa, which is lower than has previously been measured [2,3,5] and predicted [5] values for [001] textured LIGA Ni microsamples. X-ray diffraction was used to confirm that the out-of-plane texture was [001], and the lower measured value is considered to be related to the integration of porosity during the electroplating process. Calculations based on the porosity model of Krstic [8] suggest that less than 1 % of cracked spherical pore would reduce the modulus from 177 GPa to 163 GPa. Efforts to measure the residual porosity in the microsamples proved unsuccessful, but the assumption of 1 % porosity is not unreasonable for an electroplating process. As is also shown on Fig. 2, the room temperature 0.2% yield strength of the microsamples was measured to be 370MPa ± 16MPa.

The elevated temperature tensile curves are shown in Fig. 3. The Young's modulus was observed to decrease with temperature at a rate (0.11 GPa/°C) that is comparable to what has been reported for coarse-grained Ni, see Table 1. By contrast, the elevated temperature yield strength was found to be extremely temperature dependent, see Fig. 3

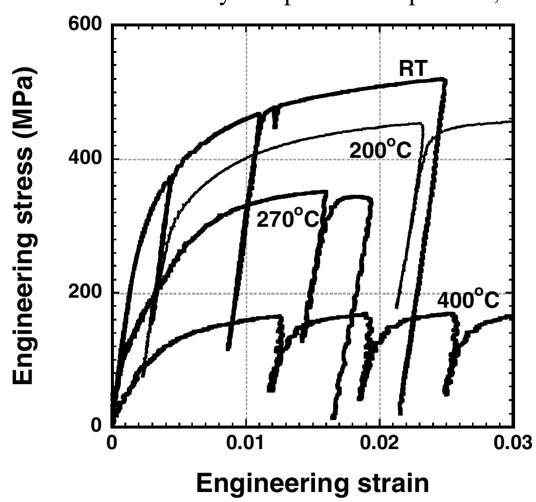

Fig. 3. Stress-strain curves of LIGA Ni at elevated temperatures.

Table 1. Young's modulus and yield strength of the LIGA Ni at temperatures.

Temperature (°C)	25	200	270	400
E (GPa)	163	137	114	126
YS (MPa)	370	323	224	143

and Table 1. The yield strength of the LIGA Ni microsamples dropped by approximately 15% at 200°C and over 60% at 400°C. Prospects for using electrodeposited pure Ni in load bearing applications above 200°C appear to be very limited.

Creep tests have been conducted at temperatures ranging from 265 to 400°C. Fig. 4 shows the LIGA Ni creep curves that consist of a normal primary creep regime, where the deformation rate decreases with time, and a steady-state regime where strain rate appears to be constant with time. The time needed to attain 0.1%, 0.2% and 0.5% creep strain, which is generally considered an important parameter for estimating creep resistance, is summarized in Table 2. Although the stress level of 110 MPa is only half of the yield strength at 265°C, considerable creep deformation was observed within the first few hours. Clearly, the elevated temperature tensile and creep strength of electro-deposited LIGA Ni will require further attention if these structures are to be used in elevated temperature MEMS applications.

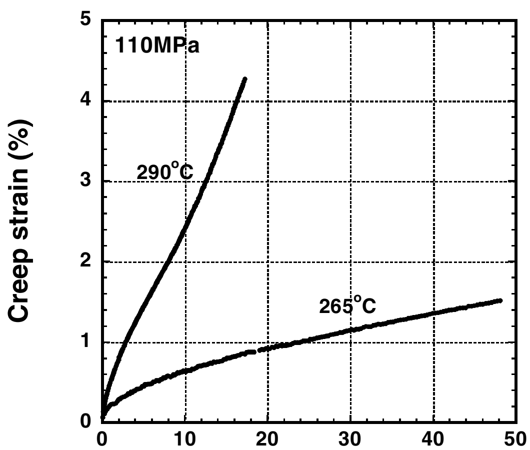

Fig. 4. Creep curves at 265 and 290°C under the stress of 110MPa. The accumulation of creep deformation is significant, even at these modest stresses and temperatures.

Table 2. Time needed to attain 0.1%, 0.2% and 0.5% creep deformation.

	265°C	290°C	400°C
$t_{0.1\%}$	0.20 hr	0.08 hr	0.006 hr
$t_{0.2\%}$	0.91 hr	0.23 hr	0.014 hr
$t_{0.5\%}$	6.20 hr	1.00 hr	0.060 hr

Figure 5 shows the stress amplitude-number of cycles to failure (S-N) curve obtained by microsample fatigue tests. The overall shape of the S-N curve for LIGA Ni is similar to what one would expect for a metal; life increases with decreasing stress. The 3 tests conducted at stresses of less than 195 MPa lasted for more that 100,000,000 cycles and these tests were stopped before the samples failed. The "run out" of these microsamples suggests that the fatigue strength (endurance limit) of LIGA Ni is approximately 195MPa. The endurance ratio (the ratio of the fatigue strength and tensile strength) for the LIGA microsamples was measured to be 0.35, which is in good agreement with endurance ratios of 0.33-0.35 that have been reported for commercial wrought nickel [9]. The experimental data for the LIGA Ni microsamples showed fatigue lives that were shorter than literature values hardened Ni but comparable to those for annealed Ni [10], see Fig. 5. It is, however, important to note that all microsamples tested in this study failed at the corner between the gage section and the ear, see Fig. 6. Modified fatigue microsamples might be expected to exhibit increased fatigue resistance, but the importance of component geometry should not be overlooked. The current fatigue tests highlight the need to incorporate component geometry when assessing the fatigue resistance of a given LIGA structure.

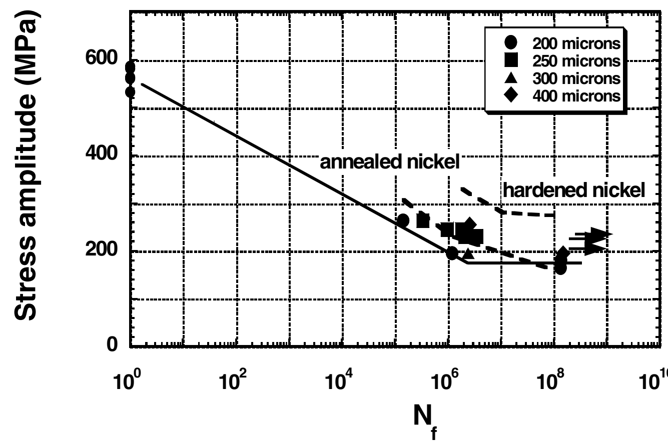

Fig 5. S-N curve of LIGA Ni plotted with wrought Ni for comparison. Note the "run out" of the three data points at 195MPa suggest a fatigue limit.

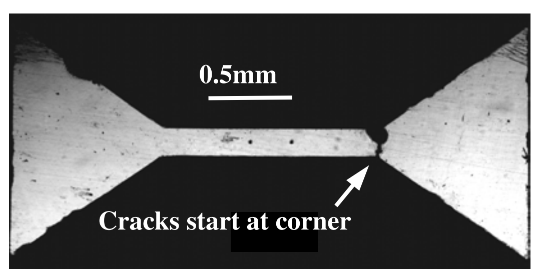

Figure 6. Microsample fractured at the corner by cyclic loading.

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